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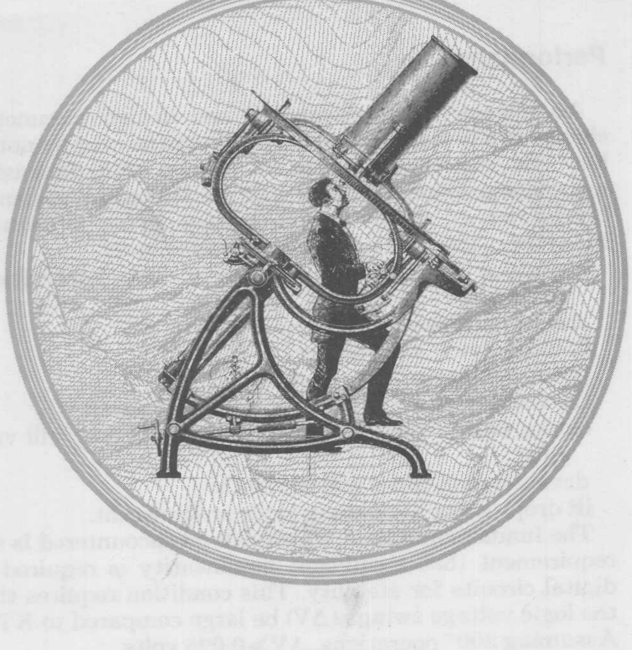

From Relays to MPU's

Robert N. Noyce
Intel Corporation

Introduction

When the IEEE Computer Society was founded twenty-five years ago, the transistor was a laboratory curiosity, and operating computers were assembled from relays or vacuum tubes. Today, a single integrated circuit far surpasses the capability of those early computers, and further progress seems inevitable. The development of semiconductor devices has depended upon a synergism with computers. This is particularly true for integrated circuits, whose development was motivated by the computer applications. With each advance in components, the computers resulting from their use reached a wider market, motivating further advances in the semiconductor technology.

Improvements in cost, reliability, and performance were the major objectives of the component development programs. Each has been improved by higher levels of complexity of integrated circuits. In assessing whether this technology is entering its maturity or its dotage, we should ask if significant additional improvements can be made in these three factors.

Costs

After design has been amortized, the production costs are made up of two basic elements: first that of the active element (today, usually silicon) and then assembly and test costs. The silicon chip cost is dependent upon the processing cost per chip and the yield of good chips. There is a limit to the size of the silicon chip which may be made with practical yield. A simple model would say that if a given size chip yielded only 10% good chips due to the inclusion of random defects, then a chip twice as large would yield only 1% good chips. (Actually the situation is not this bad, since defects are not randomly distributed.) The cost for twice the function then would be 20 times as great (twice the processing cost since twice the area of silicon is used, and 10 times the cost due to loss of yield). Clearly, if the cost of the active silicon is dominant, such a doubling of complexity would not be cost-effective, and carried to an extreme, the single transistor is the most cost-effective. (See Figure 1.)

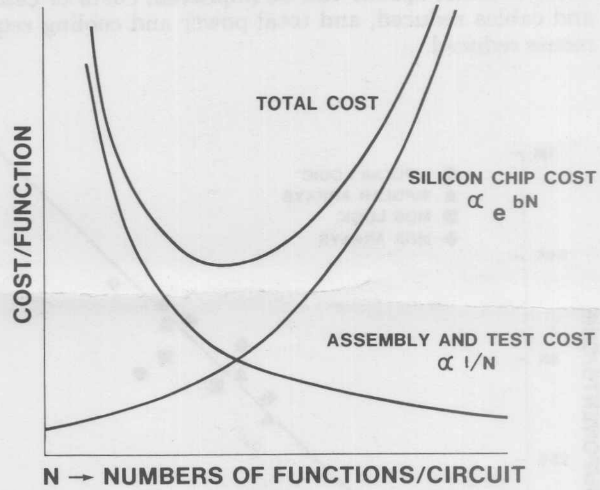

Figure 1. Cost/function vs. circuit complexity.

The other major cost element borne by the component manufacturer is that of assembling and testing the devices. Assembly is the process of putting the tiny silicon active element in a housing which includes a mechanical transition from the microscopic interconnections included in the integrated circuit to the sizes normally encountered in electronic equipment—i.e., lead separation of 10 microns to lead separation of 2500 microns or 2.5 mm respectively. As a first approximation, assembly costs are independent of the function included on the integrated circuit chip, although they will increase somewhat with the increasing number of electrical connections to large chips. Similarly, test costs increase much more slowly than the complexity of the chip being tested, although very sophisticated test equipment is required to achieve this result.

Thus, the total cost per function will be made up of two elements, one increasing with complexity of the general form ae^{bN}, representing the cost of the silicon chip, and another of the form c/N representing the cost of assembly and test, where N is the number of functions included.

This cost will have a minimum, as indicated in Figure 1. As processes for manufacturing integrated circuits have been perfected and yields of good circuits have been improved, this minimum cost point has moved to circuits of higher complexity. It has been the strategy of the semiconductor device manufacturers to supply circuits which are near this minimum at any given time.

An examination of the integrated circuits offered by the industry as a function of time provides an approximation of how the minimum cost point has moved up with time, even though a particular product offering will occur somewhat before that product is cost-effective. The minimum cost/function point has been moving up in complexity, doubling every year since the introduction of the integrated circuit (as indicated in Figure 2). If the present rates of increase of complexity were to continue, integrated circuits with 10^9 elements would be available in 20 years!

This increase in complexity has resulted in a cost savings in the subsequent assembly into computer hardware as well, since more of the total interconnections are made within the semiconductor components. Other advantages have also accrued. Because equipment can be made smaller, speeds can be improved, costs of cabinets and cables reduced, and total power and cooling requirements reduced.

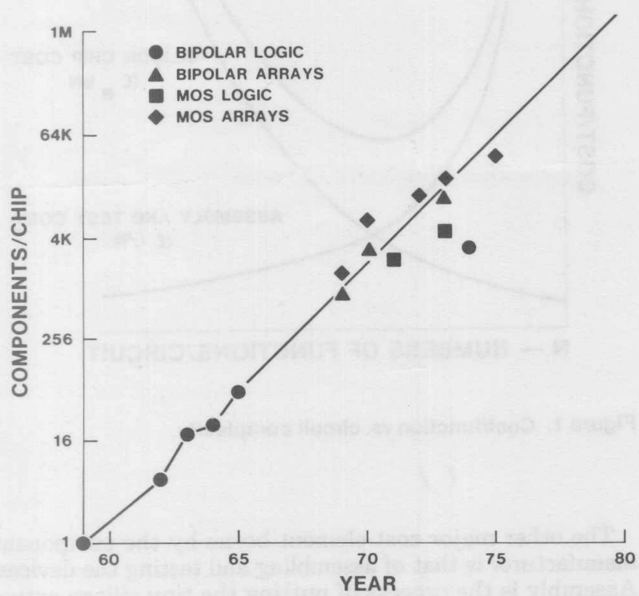

Figure 2. Circuit complexity vs. time of introduction.

Reliability

The interconnections within the integrated circuit have proven to be more reliable than the next level of interconnections, such as solder joints, or connectors. The reliability of the individual integrated circuit at time of introduction has remained nearly constant, independent of its complexity, resulting in a drastic reduction in failure rate on a per-function basis, as more complex circuits have been made available. Further improvement has been made by the reduction of the number of the less reliable solder joints and connectors. Even higher levels of integration can be expected to yield additional reliability dividends.

Performance

As dimensions decrease, all the device parameters change in a favorable direction. This can be seen by noting how the transistor parameters change with dimension, maintaining internal fields, which are limited by avalanche breakdown or, at lower voltages, quantum mechanical tunnelling. The parameters change as follows:

- operating voltages will vary as x, the characteristic dimension;
- charge densities will vary as 1/x;
- device current will vary as x;
- power density will be constant;
- the characteristic impedance will be constant;
- circuit delay times due to capacitive charging will vary as x;
- device transit times will vary as x;
- iR drops along interconnections are constant.

The fundamental limit which will be encountered is the requirement that significant nonlinearity is required in digital circuits for stability. This condition requires that the logic voltage swings (ΔV) be large compared to KT/q. Assuming 300° operations, $\Delta V \gg 0.025$ volts.

Thus, the signal levels of common logic forms can be reduced by a factor of approximately 10 before encountering this limit. A corresponding decrease in characteristic dimensions is implied with a circuit density increase of 100. Interconnect voltage drops, not a significant problem in most circuits today, will have to be improved by a smaller factor, depending on the circuit forms.

Futures

Cost, reliability, and performance all improve with smaller devices and higher levels of integration. Device size is determined by the smallest practical line widths, while the economical level of integration depends upon this factor and the practical size of silicon chips.

The minimum average dimension used in IC's is shown in Figure 3, plotted as a function of time. Production technology has moved quickly from the pre-1960 dimension of 100 microns to the 10-micron range following the introduction of photolithography as a method of defining the geometry of transistors. Steady improvement has been made since that time as equipment and methods have been improved. Recent production technology can utilize 4-micron widths, and laboratory work involves significantly smaller dimensions. These widths also define not only the size of interconnection patterns but also the source-

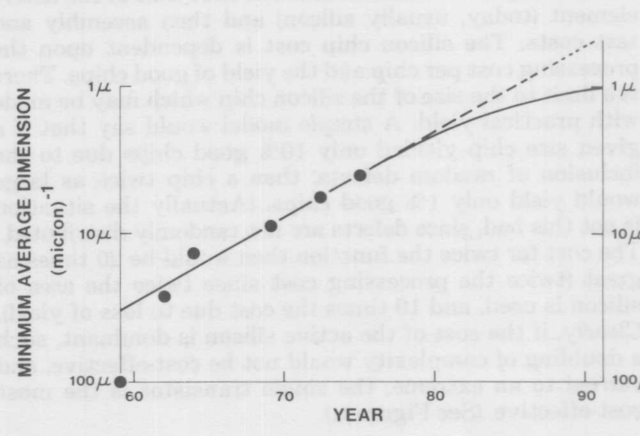

Figure 3. Minimum average dimension.

drain spacing in MOS transistors and the emitter-base contact spacing in bipolar transistors, which in turn are primary determinants of the performance of these transistors.

Minimum dimensions will continue to decrease but at a decreasing rate as optical limits are approached, reaching 2 microns in 5 years, and 1 micron in 15 years. Scaling arguments show that speed should then increase by 4 times by 1991.

Die size limitations are set by the economics of "yield." Many circuits are made, the defective ones are thrown away, and the good ones are sold. Defects can arise from many sources. The photomasks used may have pin holes in dark areas, or opaque specks in areas which should be clear. Severe defects in the basic silicon crystal can make the circuit inoperative. Dust in the photoprinting operation or other processing steps, which affects a critical spot in the circuit will cause failures. Errors of misaligning successive photoengraving steps, or of lack of control of critical dimensions and impurity concentration will make the circuit inoperative. The correction and elimination of these defects is a difficult task, and represents a major portion of the effort and expense of semiconductor device development and production.

However, there is no indication that any fundamental limit exist. Progress continues at a rate which is advantageous and can be economically justified. If defect densities are reduced as they have been in the past, chip sizes will increase by 3 times in 5 years, and 25 times in 15 years, as shown in Figure 4.

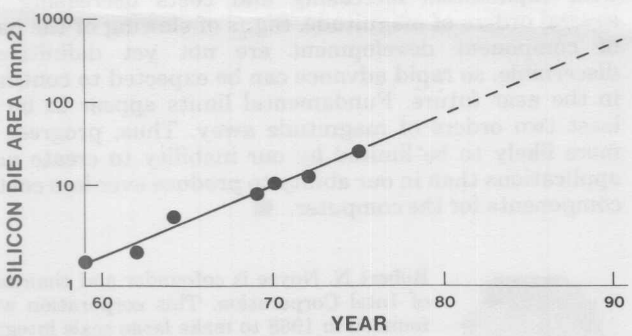

Figure 4. Silicon die area vs. time.

As a result of these factors, components providing 65 to 131 kilobits of memory with access time of 100 ns should appear in 1981 and the megabit memory chip (2^{20} bits) should appear ten years later. The use of redundancy could accelerate these times. These components should cost little more than today's memory components, or 10^{-3}¢ per bit.

For non-iterated circuits such as control logic, the level of integration will be lower due to inherent inefficiencies in packing random logic. However, the levels which could be achieved in five years would be approximately 25,000 gates, and in 10 years about 250,000 gates. These numbers exceed the gate count of today's medium and large processors, respectively. Internal gate delays of these systems would be comparable to those of today's high speed computers. If the amortization of design costs could be neglected, such logic arrays could be produced for less than $100, or a cost of less than 0.4¢ per gate in five years and less than 0.04¢ per gate in 15 years. (See Figure 5.)

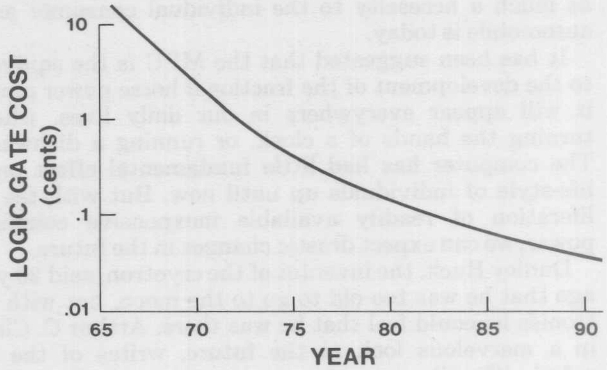

Figure 5. Logic cost vs. time.

It is perhaps obvious that with the increasing complexity of integrated circuits the design cost has been increasing. Although computer-aided design is utilized more and more widely, the cost of design of a new microprocessor is orders of magnitude more expensive than the design of a quad gate. Yet for many applications, the overall design costs can be lower, since component design includes many of the costs previously part of the equipment design. This is particularly true where the cost of the design of one microcomputer can be shared by many different applications.

The microcomputer thus serves as an example of a way out of the dilemma which the components industry encountered as LSI was becoming economically feasible. With increasing complexity the number of possible unique circuits increases enormously, and the cost of design of each increases enormously. Thus, only high-volume applications for which the design costs were small compared to the production costs could utilize this new technology. Early applications were then limited to calculators or semiconductor memories. The advent of the microprocessor unit, or MPU, neatly sidesteps this issue by leaving the uniqueness for the individual application in an area where flexibility is easy to achieve—in software or memory. Although software cost came as an unexpected expense to the components industry, it is still far less than the cost of individual design of unique circuits for each application. Furthermore, undertaking the cost of design of the MPU is less risky; with many potential applications, its market success does not depend on the success of a single program.

Improvement in production techniques of the MPU will result naturally from the high-volume production of semiconductor memories. The complexity of the MPU can be expected to follow that of semiconductor memories with a time lag of a year or two needed for architectural and logic design of the more complex MPU. The eventual cost, if large markets are developed, will be no more than any LSI circuit of similar size and complexity, after amortization of design and software cost.

The implications of this cost decline for sophisticated computing power are enormous. We have had a glimpse of the changes which can be expected from the development of the calculator market. Ten years ago it would have been difficult to predict that the calculator would displace the slide rule. Today, it is equally as difficult to predict what displacements are in store for the next decade or two.

The capabilities of the microcomputer system, which can be purchased for the price of an automobile, is comparable to that of a medium-scale computer of a decade

ago. And tomorrow the personal computer could become as much a necessity to the individual consumer as the automobile is today.

It has been suggested that the MPU is the equivalent to the development of the fractional horse power motor—it will appear everywhere in our daily lives, whether turning the hands of a clock, or running a dishwasher. The computer has had little fundamental effect on the life-style of individuals up until now. But with the proliferation of readily available inexpensive computing power, we can expect drastic changes in the future.

Dudley Buck, the inventor of the cryotron, said 20 years ago that he was too old to go to the moon, but with electronics he could feel that he was there. Arthur C. Clarke, in a marvelous look at the future, writes of the telesafari, "Don't commute, communicate!"[1] The author knows of more than one case where a computer terminal has displaced an automobile for commuting to work.

Other human activities can be expected to change. For entertainment, we might compose and perform our own symphonies, or operas, or write our own motion pictures. We could provide the individual with access to the libraries of the world from his armchair, or programmed instruction on the subject of his choice. His typewriter could displace the postal service, as his completed letter is automatically typed out on the addressee's typewriter. As costs decrease, the use of the computer, which has been the province of large organizations, will extend to individuals, first to the few, then to many. Long-hoped-for miracles of restoring sight (or its near equivalent) to the blind should become economically advantageous. On a broader scale, the work force in service activities, more than half of the total work force, will be helped by the amplification of intelligence using the computer, just as manual labor was enhanced by using power equipment.

The engineering profession has progressed by building on past experience, taking past accomplishments as a starting point to set new objectives. The results of yesterday's research projects becomes the handbook data for today's design activities. We have seen this progression in the development of semiconductor technology in the last 25 years, as the design activities progressed to higher levels. Thus, pushing to higher performance levels, the results of transistor design were assumed as the integrated circuit was designed. These elemental circuits were assumed as MSI was designed, and the MSI building blocks were used to produce LSI designs. Similarly, the basic processing techniques of material purification, alloying, diffusion, photolithography, epitaxial growth, and ion implantation were successively assumed as new production techniques were being developed.

The background knowledge useful to the practitioner has shifted, as the field has matured. Initially, the fundamental physics and chemistry of semiconductor materials were key as problems were centered in these areas. As solutions to these problems were reached, basic circuit theory became more critical when transistors were designed to specific applications. Circuit theory gave way to logic design, then to systems architecture and software as the pivotal points where the greatest progress was made.

Today, we see the integration of all disciplines in design of new systems with each contributing to the new design. The future progress will be dependent upon reaching the frontiers via the paths of previous work, or upon finding errors or omissions in the work of earlier pathfinders. Success will be dependent upon detailing areas which have been explored in a cursory fashion, or upon having a broad understanding of the potential applications, and methods available to satisfy these requirements, including not only the devices themselves but the software necessary to make these devices useful.

Industry structure

Even the structure of the electronics industry has been changed as a result of higher levels of integration. Activities once considered quite independent of component design now are becoming an integral part of the component manufacturer's activity. Much of circuit design has been included in IC development, and much of architectural and software design is now included in the development of the MPU.

Stable applications of LSI, such as the calculator, have become the province of the companies which are integrated from device design to end product. We may expect that other products will follow as equipment manufacturers assume LSI design responsibility, or companies with the LSI capabilities find new areas of application for their capabilities. I believe, however, that the greatest advances will result from the traditional synergism of the computer and component disciplines, each concentrating in its own areas of expertise, while trying to understand the prospects and problems of the other. The component discipline approaches the problems from the "how to" point of view; the computer discipline from the "what to do" point of view. Both are necessary to find the optimum solution to the problem of satisfying each application.

The combined progress of computer and component technology over the past 25 years has been astounding, with capabilities increasing and costs decreasing by several orders of magnitude. Signs of slowing of the pace of component development are not yet definitively discernible, so rapid advance can be expected to continue in the near future. Fundamental limits appear to be at least two orders of magnitude away. Thus, progress is more likely to be limited by our inability to create new applications than in our ability to produce ever less costly components for the computer. ■

1. Arthur C. Clarke, "Communication in the Second Century of the Telephone," *Technology Review* (MIT), Vol. 78, #6 (1976) p. 33.

Robert N. Noyce is cofounder and chairman of Intel Corporation. This corporation was founded in 1968 to make large scale integration a reality.

Prior to forming Intel Corporation, he helped found Fairchild Semiconductor Corporation. As research director at Fairchild, he was responsible for the initial development of the silicon mesa and planar transistor lines, later serving as vice president and general manager of the corporation. Before joining Fairchild, he was associated with Shockley Semiconductor Laboratory where he worked in the design and development of silicon transistors.

Noyce's contributions to the development of diffused silicon devices include the first silicon diffused planar transistor, the first monolithic IC's in production, gold doping of semiconductor devices, the first multichip packaging, and PNP double diffused transistors. He holds 16 patents on semiconductor methods, devices and structures, including applications of photoengraving to semiconductors, and diffused-junction isolation for IC's. He also holds the basic patent relating to metal interconnect schemes.

He received his B.A. in physics and mathematics from Grinnell College (Iowa) and his Ph.D. in physical electronics from M.I.T.

Dr. Noyce has been cited by the National Association of Manufacturers in recognition of his contribution to mankind through scientific research, and he has received the Stuart Ballantine Medal from the Franklin Institute. He is a member of the National Academy of Engineering, a Fellow of the IEEE, and a member of the American Physical Society.